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PATENT APPLICATION

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of:	)	
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KIERAN GERARD LARKIN ET AL.	)	
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Appln. No.: 09/735,809	)	
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Filed: December 14, 2000	)	
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For: METHOD AND APPARATUS	)	
FOR UNIFORM LINEAL	:	
MOTION BLUR ESTIMATION	)	
USING MULTIPLE EXPOSURES	:	March 19, 2001

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Commissioner for Patents
Washington, D.C. 20231

CLAIM TO PRIORITY

Sir:

Applicants hereby claim priority under the International Convention and all rights to which they are entitled under 35 U.S.C. § 119 based upon the following Japanese Priority Applications:

PQ 4641 filed on December 14, 1999
PQ 4643 filed on December 14, 1999

Certified copies of the priority documents are enclosed.

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Applicants' undersigned attorney may be reached in our New York office by telephone at (212) 218-2100. All correspondence should continue to be directed to our new address given below.

Respectfully submitted,

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I, KAY WARD, ACTING MANAGER EXAMINATION SUPPORT AND SALES hereby certify that annexed is a true copy of the Provisional specification in connection with Application No. PQ 4643 for a patent by CANON KABUSHIKI KAISHA filed on 14 December 1999.

WITNESS my hand this
Twenty-first day of December 2000

K Ward

KAY WARD
<u>ACTING MANAGER EXAMINATION SUPPORT AND SALES</u>

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S&F Ref: 459925

ORIGINAL

AUSTRALIA

Patents Act 1990

<u>PROVISIONAL SPECIFICATION FOR THE INVENTION ENTITLED</u>:

Apparatus for Uniform Lineal Motion Blur Estimation Using Multiple Exposures

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This invention is best described in the following statement:

APPARATUS FOR UNIFORM LINEAL MOTION BLUR ESTIMATION USING MULTIPLE EXPOSURES

Technical Field of the Invention

The present invention relates generally to estimating motion from image blur and, in particular, to an image sensor with a capability to capture multiple concurrent (overlapping in time) images which forms part of a system used to estimate a uniform lineal motion using error minimisation.

Background Art

Known arrangements for performing motion estimation of video images typically use one of the following methods:

(i) estimation of illumination partial derivatives in combination with optical flow;

(ii) local (block based) calculation of a cross-correlation between successive images and using maxima to estimate the shift between images; or

(iii) estimation of the motion blur in any one image (using a variety of methods such as blind de-convolution, maximum likelihood estimation etc) to then use as a motion vector in optical flow.

The above arrangements each suffer from the disadvantage of being time consuming and not necessarily very robust or reliable. For example, in video applications, at least two frame images are required to provide a single estimation of blur between the images. Further, since conventional video capture devices capture the frame images very quickly, and spend much of the time associated with the frame period outputting the image data, existing devices have no ability to estimate motion or blur within the frame (ie. the blur that occurred during the capture of the frame).

Motion estimation is typically used for video coding, object detection and tracking as well as video content analysis.

Disclosure of the Invention

It is an object of the present invention to substantially overcome, or at least ameliorate, one or more disadvantages of existing arrangements.

According to a first aspect of the invention, there is provided apparatus for estimating motion of a moving image, said apparatus comprising:

an image sensor for capturing pixels of at least first and second images in which one of said images is sampled during a formation of at least one other of said images;

means for comparing said images to determine at least one motion vector for association with one of said images.

According to a second aspect of the invention, there is provided apparatus for estimating motion of a moving image, said apparatus comprising:

an image sensor for capturing pixels of at least first and second images in which one of said images is sampled after sampling of at least one other of said images, the sampling of said one image occurring before an outputting from said sensor of image data of said other image;

means for comparing said images to determine at least one motion vector for association with one of said images.

According to a first aspect of the invention, there is provided apparatus for estimating motion of a moving image, said apparatus comprising:

an image sensor for capturing pixels of at least first and second images characterised in that images data of each of said images is acquired prior to an outputting of said image data from said sensor;

means for comparing said images to determine at least one motion vector for association with one of said images.

Other aspects of the invention are also disclosed.

Brief Description of the Drawings

A number of preferred embodiments of the present invention will now be described with reference to the drawings, in which:

Fig. 1 shows blur functions b_1 and b_2 representing lineal (motion) blur of spatial extent $2a_1$ and $2a_2$ respectively occurring in a direction at angle θ to the x axis;

Figs. 2A and 2B illustrate the x' component of the respective blur functions b_1 and b_2 , resulting from two uniform exposures with the same start times, but with the one exposure twice the duration of the other;

Figs 3A and 3B illustrate an interpretation of error minimisation;

Fig. 4 is a schematic block diagram of an apparatus for blur estimation;

Fig. 5 is a schematic block diagram of a structure of a CMOS sensor used to capture blurred images g_1 and g_2 of Fig. 4;

Fig. 6 is a timing sequence to be used with the CMOS sensor of Fig. 5 to capture the two overlapping blurred images g_1 and g_2;

Fig. 7 is a schematic block diagram of an embodiment of a correlator that may be used in the apparatus of Fig. 4 for blur estimation;

Fig. 8 is a schematic block diagram of another embodiment of a correlator that may be used in the apparatus of Fig. 4 for blur estimation;

Fig. 9 is a schematic block diagram of an embodiment of a extreme locater that may be used in the apparatus of Fig. 4 for blur estimation;

Figs. 10A to 10E provide comparisons between image capture according to prior art arrangements and those according to embodiments of the present invention; and

Figs. 11 and 12 depict capture devices according to embodiments of the invention.

Detailed Description including Best Mode

Prior to the description of the preferred embodiments of this invention, motion estimation using blur analysis will first be discussed.

Consider an ideal two dimensional digital image signal, represented as a function $f(x,y)$, where x and y are the horizontal and vertical image coordinates. The image signal $f(x,y)$ is defined for all integer values of x and y, and undefined for all non-integer values of x and y. The digital image signal $f(x,y)$ is typically obtained by sampling an analog image, for instance, an image on film.

In practice, this ideal image signal $f(x,y)$ is distorted by various image degradations. In this specification, image blurring is considered as well as additive noise. The image blurring to be considered is a special form of blur, namely uniform lineal blur typically caused by motion in a plane at an oblique angle to a line of sight of a camera used for capturing the image. The blurred image is represented as g_1. In the preferred embodiment of the invention, two different blurred images are used, g_1 and g_2.

The blurred images g_1 and g_2 can be represented as the result of a pair of blur functions b_1 and b_2 operating on the image signal $f(x,y)$. The blurred images g_1 and g_2 can therefore be represented using the convolution ($*$) operator as:

$$g_1(x,y)=f(x,y)*b_1(x,y)+n_1(x,y) \tag{1}$$

$$g_2(x,y)=f(x,y)*b_2(x,y)+n_2(x,y) \tag{2}$$

where n_1 and n_2 are additive noise signals.

An assumption is made that the motion is lineal and uniform over the image region under consideration. The blur functions b_1 and b_2 represent one dimensional (motion) blur of spatial extent $2a_1$ and $2a_2$ respectively occurring in a direction at angle θ to the x axis as illustrated in Fig. 1. Consequently the blur functions b_1 and b_2 can be represented as follows:

$$b_1(x,y)=\frac{1}{2a_1}rect(\frac{x'}{2a_1}).\delta(y') \tag{3}$$

$$b_2(x,y)=\frac{1}{2a_2}rect(\frac{x'-x'_0}{2a_2}).\delta(y'-y'_0) \tag{4}$$

wherein

$$rect\left(\frac{p}{2s}\right)= \begin{cases} 0 \text{ for } p>s, & \text{or} \\ 1 \text{ for } |p|<s, & \text{and} \end{cases} \tag{5}$$

$\delta(p)$ is the Dirac delta function such that:

$$\int_{-\infty}^{\infty} f(x).\delta(x-x_0)dx=f(x_0) \tag{6}$$

wherein f is any function. (x',y') are rotated coordinates having the following relations:

$$\left.\begin{aligned} x' &= +x\cos(\theta)+y\sin(\theta) \\ y' &= -x\sin(\theta)+y\cos(\theta) \end{aligned}\right\} \tag{7}$$

As will be apparent from Fig. 1, the rotated coordinates have one coordinate aligned with the direction of blur. The centre of the second blur function b_2 is offset by an amount (x_0, y_0) from the centre the first blur function b_1. In essence, the blur functions b_1 and b_2 convert all point intensities of the image signal $f(x,y)$ into linear smears of length directly proportional to the exposure time and the image velocity.

The two dimensional Fourier transform $G(u,v)$ of an arbitrary signal $g(x,y)$ is defined as:

$$G(u,v) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(x,y)\exp(-2\pi i[ux+vy])dxdy \qquad (8)$$

where u and v are the spatial frequency coordinates. Consequently, the transforms G_1 and G_2 of the blurred images g_1 and g_2 can be written as:

$$G_1(u,v)=F(u,v).B_1(u,v) + N_1(u,v) \qquad (9)$$

$$G_2(u,v)=F(u,v).B_2(u,v)+N_2(u,v) \qquad (10)$$

The discrete Fourier transforms B_1 and B_2 of the blur functions b_1 and b_2 have a simple (one dimensional) form when expressed in relation to rotated frequency axes, namely:

$$\left.\begin{aligned} u' &= +u\cos(\theta) + v\sin(\theta) \\ v' &= -u\sin(\theta) + v\cos(\theta) \end{aligned}\right\} \qquad (11)$$

$$B_1(u,v) = \frac{\sin(2\pi u'a_1)}{2\pi u'a_1} \qquad (12)$$

$$B_2(u,v) = \frac{\sin(2\pi u'a_2)}{2\pi u'a_2}.\exp(-2\pi i[u'x_0']) \qquad (13)$$

From Equations (9), (10), (12) and (13), the transforms G_1 and G_2 can be rewritten as:

$$G_1(u,v) = F(u,v).\frac{\sin(2\pi u'a_1)}{2\pi u'a_1} \qquad (14)$$

$$G_2(u,v) = F(u,v).\frac{\sin(2\pi u' a_2)}{2\pi u' a_2}.\exp(-2\pi i[u' x_0'])+N \tag{15}$$

For simplification, the additive noise spectra terms N_1 and N_2 in Equations (9) and (10) have been substituted by a single noise spectrum term N in Equation (15).

Figs 2A and 2B illustrate the x' components of the respective blur functions b_1 and b_2 resulting from two uniform exposures, starting on the same time, but with the one exposure twice the duration of the other. This particular relationship between the two exposures results in the following parameters:

$$\left.\begin{aligned} a_1 &= a \\ a_2 &= 2a \\ x_0' &= a \\ y_0' &= 0 \end{aligned}\right\} \tag{16}$$

Applying these parameters to Equations (14) and (15) gives the Fourier spectra:

$$G_1(u,v) = F(u,v).\frac{\sin(2\pi u' a)}{2\pi u' a} \tag{17}$$

$$G_2(u,v) = F(u,v).\frac{\sin(4\pi u' a\ )}{4\pi u' a}.\exp\left(-2\pi i u' a\right) + N(u,v) \tag{18}$$

From Equations (17) and (18), the noise term $N(u,v)$ is as follows:

$$N(u,v) = G_2(u,v) - G_1(u,v).\cos(2\pi u' a).\exp(-2\pi i u' a) \tag{19}$$

A modulus-squared error or "deviation" function t can be expressed as a function of the blur parameter a:

$$\begin{aligned} t(a) &= \int\int_R \left|N(u,v)\right|^2 du dv \\ &= \int\int_R \left|G_2(u,v) - G_1(u,v).\cos(2\pi u' a).\exp(-2\pi i u' a)\right|^2 du dv \end{aligned} \tag{20}$$

However, Equation (20) can be further expanded as:

$$t(a) = \iint_R \left\{|G_2|^2 + |G_1|^2 \cos^2(2\pi u'a)\right\} dudv - \iint_R \left(G_2^* G_1.\exp(-2\pi i u'a) + G_1^* G_2.\exp(2\pi i u'a)\right).\cos(2\pi u'a) dudv \quad (21)$$

$$\begin{aligned} &= \iint_R \left\{|G_2|^2 + \frac{|G_1|^2}{2}\right\} dudv \\ &+ \frac{1}{2} \iint_R |G_1|^2 \cos(4\pi u'a) dudv \\ &- \frac{1}{2} \iint_R \left(G_2^* G_1 + G_1^* G_2\right) dudv \\ &- \frac{1}{2} \iint_R \left\{G_2^* G_1.\exp(-4\pi i u'a) + G_1^* G_2.\exp(4\pi i u'a)\right\} dudv \end{aligned} \quad (22)$$

Applying a transformation:

$$\left.\begin{aligned} a\cos\theta &= X \\ a\sin\theta &= Y \end{aligned}\right\} \quad (23)$$

to Equation (22) results in the following:

$$\begin{aligned} t(a,\theta) &= \varepsilon(X,Y) \\ &= \iint_R \left\{|G_2|^2 + \frac{|G_1|^2}{2}\right\} dudv \\ &- \frac{1}{2} \iint_R \left\{G_2^* G_1 + G_1^* G_2\right\} dudv \\ &+ \frac{1}{2} \iint_R |G_1|^2 \cos(4\pi[uX + vY]) dudv \\ &- \frac{1}{2} \iint_R \left\{G_2^* G_1.\exp(-4\pi i[uX + vY]) + G_1^* G_2.\exp(4\pi i[uX + vY])\right\} dudv \end{aligned} \quad (24)$$

Because the blurred images g_1 and g_2 are both real functions, the following properties exist:

$$\begin{aligned} G_n^*(u,v) &= G_n(-u,-v) \\ |G_n(-u,-v)| &= |G_n(u,v)| \end{aligned} \quad (25)$$

The full (or at least symmetrical) limits in frequency space allow the last two terms of Equation (24) to be joined.

$$\begin{aligned}
&\varepsilon(X,Y)= \\
&\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left\{\left|G_2(u,v)\right|^2+\frac{1}{2}\left|G_1(u,v)\right|^2\right\}dudv \\
&-\frac{1}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left\{G_2^*(u,v)G_1(u,v)+G_1^*(u,v)G_2(u,v)\right\}dudv. \\
&+\frac{1}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left|G_1(u,v)\right|^2\exp\left(4\pi\left[uX+vY\right]\right)dudv \\
&-\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}G_1(-u,-v)G_2(u,v).\exp\left(4\pi i\left[uX+vY\right]\right)dudv
\end{aligned} \tag{26}$$

Only the last two terms of Equation (26) are functions of X and Y. These are therefore the only terms determining where the minimum of the deviation function $\varepsilon(X,Y)$ is located. In particular, the last two terms can be recognised as having the form of auto and cross-correlation functions.

$$\begin{aligned}
&\frac{1}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left|G_1(u,v)\right|^2\exp\left(4\pi\left[uX+vY\right]\right)dudv \\
&-\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}G_1(-u,-v)G_2(u,v).\exp\left(4\pi i\left[uX+vY\right]\right)dudv \\
&=\frac{1}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}G_1(-u,-v).\left\{G_1(-u,-v)-2G_2(u,v)\right\}.\exp\left(4\pi i\left[uX+vY\right]\right)dudv
\end{aligned} \tag{27}$$

Equation (27) can be interpreted as the convolution of $g_1(-x,-y)$ with the difference of $g_1(-x,-y)$ and $2g_2(x,y)$ evaluated at coordinates (X',Y'), where

$$\left.\begin{aligned} X' &= 2X \\ Y' &= 2Y \end{aligned}\right\} \tag{28}$$

Blur functions having such a result are illustrated in Figs. 3A and 3B.

It follows from the foregoing that where two images are captured in direct association, either overlapping, immediately adjacent or closely adjacent with respect to capture time, and assuming linear motion over each area of interest, the blur in either image may be determined. With conventional arrangements this requires two image captures, generally separated by one field or frame period, to determine motion vectors.

The present inventors have realised that where more than one image can be captured with a field or frame period, motion blur may therefore be estimated for at least that field or frame. Thus motion vectors may be obtained from multiple sub-field or sub-frame images, thereby improving motion vector accuracy and associating such vectors with a single (traditional) field or frame image, as opposed to a pair of such traditional images. In this fashion the motion vector obtained much more accurately represents the motion that occurred during the capture of the respective image, as opposed to the motion that occurred between capture of adjacent traditional field/frame images.

Fig. 4 illustrates a block diagram of apparatus 9 for estimating the blur parameters of blurred images according to an embodiment of the present invention. The apparatus 9 has an image sensor 10, preferably formed in CMOS technology, for capturing the blurred images g_1 and g_2, a plurality of correlators 20 and 30 for performing autocorrelation of the blurred image g_1 and cross-correlation between the two images g_1 and g_2 respectively, an error function calculator 40 for evaluating an error function t over all possible displacements using the results from the correlators 20 and 30, and an extreme locater 50 for finding the displacement with the minimum value for the error function t.

The operation of the image sensor 10, as implemented with CMOS technology, will be further explained with references to Figs. 5 and 6. Fig. 5 shows a circuit layout of a part 12 of the image sensor 10, the part 12 being arranged to capture a single pixel of the digital image signal $f(x,y)$ by means of a pixel cell 60.

The pixel cell 60 is formed of a photodiode 63 which acts as an image pixel sensor and which connects to a transistor 64 to discharge a parasitic capacitor Cp according to the intensity of illumination falling upon the photodiode 63. The parasitic capacitor Cp may be formed by a floating diffusion. A transistor switch 62, operated by a reset signal 'res', acts to reset the capacitor Cp by applying a supply rail potential to the capacitor Cp. A signal "TX"

is applied to the parasitic capacitor Cp enabling the capacitor Cp to discharge through the operation of the photodiode 63. It will be appreciated therefore that the sensor 10 operates according to negative logic principles where the charge on the capacitor Cp is the inverse of the light intensity-duration function applied to the photodiode 63. A select signal 'sel' operates a transistor switch 65a which, together with a source-follower transistor 65b, couples the voltage on the parasitic capacitor Cp to a pixel data bus 61. The duration that the signal 'TX' is applied is usually called the exposure time, and the charge of the parasitic capacitor Cp is the value of the pixel cell 60. A number of the pixel cells 60 may be connected to the pixel data bus 61.

In order to provide a sequence of output pixel values of an image, a switching arrangement 66 is provided to couple such values to an output 67 of the part 12. The sequence may, for example, be a raster sequence.

Signals "N1" and "N2" are applied to transistor switches SW1 and SW3, causing them to conduct thereby providing for noise charge values to be stored on capacitors C1 and C3 respectively. Such noise values are representative of circuit noise and are available on the pixel data bus 61 when the 'sel' signal of each of the cells 60 connected to the bus 61 are all disabled or not selected.

Signals 'S1' and 'S2' are applied to turn ON switches SW0 or SW2 respectively, so that capacitors C0 and C2 are selectively charged according to the pixel value as present on the pixel bus 61.

Signals 'HST0'and 'HST1" are applied to turn ON switch pairs SW4 and SW5, and SW6 and SW7 respectively. The switches SW5 and SW7 act to couple the noise values on the capacitors C1 and C3 respectively to a buffer 'bufn', while the pixel values present on the capacitors C0 and C2 are coupled via operation of the switches SW4 and SW6 respectively to a buffer 'bufs'. A differential amplifier 'diffamp', connected to the buffers 'bufn' and 'bufs', finds the difference between the two signals to output a signal indicative of the light fallen upon the photodiode 63.

By forming the image sensor 10 as a matrix of pixel cells 60 formed in rows (lines) and columns, overlapped double sampling of an image that gives rise to blur functions illustrated

in Figs. 2A and 2B, can be achieved using the circuit 12 of Fig. 5 by applying to the circuit 12 a signal sequence as shown in Fig. 6.

When a signal 'sel0' is asserted, all the pixel cells 60 in row 0 of the matrix are enabled, and each drive a corresponding pixel data bus 61 in the corresponding column.

The signal 'res' is then asserted, causing all the pixel cells 60 in line 0 to be reset, and leaving each cell 60 driving a noise value on the corresponding pixel data bus 61.

As the signal 'res' id de-asserted, the signals 'N1' and 'N2' are then asserted to latch the noise values into capacitors C1 and C3. The signal 'TX' is then asserted for a period 'Tex'. During the period 'Tex', all the pixel cells 60 in line 0 discharge their corresponding parasitic capacitors Cp according to the light intensity on line 0. The signal 'S1' is asserted in the middle of the exposure time to store the pixel values at that time in the respective capacitors C0. At the end of the exposure time 'Tex', the pixel values at that time are stored in capacitors C2 by asserting signal 'S2'. The signal 'HST0' is then asserted to switch on SW4 and SW5 to find the true values of the pixels during the first half of exposure time 'Tex'. The signal 'HST1' is asserted to switch on SW6 and SW7 to find the true values of the pixels during the second half of exposure time 'Tex'. The signals 'HST0' and 'HST1' are asserted progressively along line 0 for each pixel to output a sequence of pixel values for the line. This is repeated until all the pixels in line 0 are read.

Such a mode of operation results in a pixel sequence as follows, for n pixels in the line:

Pixel_1_half, Pixel_1_full, Pixel_2_half, Pixel_2_full, ... Pixel_n_full.

A next line (line 1) is selected by asserting 'sel1', and the above is repeated.

Alternatively, the mode of operation may bè altered to provide the following sequence:

Pixel_1_half, Pixel-2_half ... Pixel_n_half, Pixel 1_full, Pixel 2_full, ... Pixel_n_full.

It will be apparent from the forgoing that where S1 is activated at the middle of TX and S2 at the end, the first image obtained by virtue of S1, for a stationary target which presents no blur, will have half the intensity of the second image obtained at S2. As such, any image derived at S1 will include, for all intents and purposes, the same components of the image obtained at S2. This is to be contrasted with prior art arrangements where single frames or

fields are captured one after the other in which case the entire sensor reset and newly illuminated.

Fig. 7 shows one embodiment of a circuit 69 for use as part of the correlator 20 or the correlator 30. In this embodiment, the circuit 69 has registers 70 to 73 for holding the pixel data of a first image p to be correlated and one cyclic barrel shifter 74 to 77 for each row. The cyclic barrel shifters 74 to 77 rotate the pixel data to perform the convolution. The circuit 69 also has one cyclic barrel shifter 78 to 81 for each column to rotate the pixel data from the row barrel shifters 74 to 77. The barrel shifters 78 to 81 output to corresponding groups of multipliers 82 for multiplying the rearranged pixel data with pixel data from another image source q, and an adder 83 for adding the products from the multipliers 82 together. When the circuit 69 is used as the auto-correlator 20 of Fig. 4, the input images p and q are derived from the same input image source. Although not shown in Fig. 7, the q input may be deposited into registers in a manner akin to the p input, thereby enabling correction for any timing issues.

The circuit 69 commences operation by shifting into the registers 70 to 73 the pixel data from the image p. After the whole image p is shifted in, the barrel shifters 74 to 77 are configured to rearrange the pixel data of image p to calculate various correlation values. In the situation where the barrel shifters 74 to 77 are not shifting its input p, the correlator calculates $(p \circ q)(0,0)$. With the row barrel shifters 74 to 77 shifted one position to the right, and the column barrel shifters 78 to 81 not shifted, the circuit 69 calculates $(p \circ q)(0,1)$, which is the same as $(p \circ q)(0, N-1)$, with N being the number of rows in the images p and q. When the row shifters 74 to 77 are not shifting their input p, and the column shifters 78 to 81 are shifting their input q by k positions to the right, then the circuit 69 calculates both $(p \circ q)(k,0)$ and $(p \circ q)(M-k,0)$, with M being the number of columns in the images p and q.

In terms of hardware, for images of dimension MxN pixel cells 60, this embodiment of the circuit 69 requires:

- 2xMxN registers to hold all the pixel values of the two images p and q;
- M N-input row barrel shifters to shift the pixel values in the rows;

- N M-input column barrel shifters to shift the outputs from the row barrel shifters;
- MxN multipliers to multiply the rearranged pixel values of one image p with pixel values from the other image q;
- Mx(N-1) 2-input adders (or a single MxN input adder) to add the products of the multipliers; and
- barrel shifter control logic.

Fig. 8 shows a second embodiment of a correlator circuit 85. This embodiment uses Fourier Transforms to calculate correlations between images c and d. Using the correlation theorem,

$$c(x,y) \circ d(x,y) \Leftrightarrow C^{*}(u,v)D(u,v) \tag{29}$$

the cross-correlation of the two images c and d can be calculated by inputting pixels from the images c and d into respective row buffers 86. A Fourier transform 87 is then performed on both images c and d to obtain their Fourier coefficients C and D. The coefficients are multiplied 88 on a one by one basis and an inverse Fourier transform 89 is performed on the output of the multiplier 88. The results of the inverse transform 89 comprise cross correlation coefficients that are retained in a result buffer. Again, for an autocorrelator implementation, the inputs c and d are connected to the same image input.

The implementation of the 1-dimensional Fourier transform and inverse Fourier transform blocks are well known to persons in the art.

In terms of hardware, to correlate two images c and d of dimension MxN, the arrangement 85 of Fig. 8 requires:

- two N-pixel buffers to store one row of the incoming data;
- two blocks of logic performing 1-dimensional Fourier transform on the row of N pixels. The amount of logic required may be determined from the value of N;
- two blocks of logic performing 1-dimensional Fourier transform on the row of M coefficients. The amount of logic required may be determined from the value of M;

- three transposing memories to hold MxN pixel values/coefficients;
- three memory blocks to hold MxN Fourier coefficients, two for the input of the multiplier and one for the product;
- one block of logic performing 1-dimensional inverse Fourier transform on M coefficients;
- one block of logic performing 1-dimensional inverse Fourier transform on N coefficients; and
- one N-entry buffer to hold one row of the correlation coefficients.

The error function calculator 40 of Fig. 4 receives the correlation results from the correlators 20 and 30 and calculates the error values based on the foregoing equations derived above. The error calculator 40 may be formed in hardware by an appropriate combination of adders and multipliers and associated logic, or alternatively implemented in software.

The evaluation of the error function for every point in the domain of the correlation function provides identification of two minima in the error function, one opposite to the other with respect to the origin. Either one of these minima can indicate the displacement (blur) between the two images. To find these minima, all the error function values are searched for the smallest error function value, and the displacement that result in the minima are recorded. This takes MxN clock cycles, where M is the number of rows (lines) in the image and N is the number of columns in the image.

However, to increase the accuracy in the estimation, the true minimum in sub-pixel precision can be found. A typical method used is curve fitting, which is a method well known to people skilled in the art.

Before the implementation of such an extreme locater is considered, the theory behind the extreme locator will be examined. Consider for example a $(2n+1)$x$(2n+1)$ neighbourhood around pixel (x,y) wherein the neighbourhood is defined by all the pixels in a square with corners at $(x-n,y-n)$, $(x-n,y+n)$, $(x+n,y+n)$ and $(x+n,y-n)$. Typically n=1 or 2. A quadratic surface can be fitted locally around the minimum, after which a location of a best-fit surface minimum is calculated. This is effectively interpolation of the minimum position.

A second order surface can be expressed as:

$$P(x,y) = a_{00} + a_{10}x + a_{01}y + a_{11}xy + a_{20}x^2 + a_{02}y^2 \tag{29}$$

which represents a local region with an elliptical paraboloid of arbitrary orientation and axes. A 'least squares fit' is applied to the function $f(x,y)$ on a discrete grid of points:

$$\left.\begin{aligned} x &= m\Delta \\ y &= n\Delta \end{aligned}\right\} \tag{30}$$

expressed as:

$$E = \sum_{n=-N}^{N} \sum_{m=-M}^{M} \left[f(m\Delta, n\Delta) - P(m\Delta, n\Delta)\right]^2 \tag{31}$$

Stationary points for all values of k and l are found by:

$$\frac{\partial E}{\partial a_{kl}} = \sum_{n=-N}^{N} \sum_{m=-M}^{M} (m\Delta)^k (n\Delta)^l \left[f(m\Delta, n\Delta) - P(m\Delta, n\Delta)\right] = 0 \tag{32}$$

Six simultaneous equations can be derived. Typically $M=N=1$ or 2.

$$\sum_n \sum_m m^k n^l f_{m,n} = \sum_n \sum_m m^k n^l P_{m,n} \tag{33}$$

Equation (33) is expanded into:

$$\begin{pmatrix} \sum_n\sum_m f_{m,n} \\ \sum_n\sum_m m f_{m,n} \\ \sum_n\sum_m n f_{m,n} \\ \sum_n\sum_m m^2 f_{m,n} \\ \sum_n\sum_m mn f_{m,n} \\ \sum_n\sum_m n^2 f_{m,n} \end{pmatrix} = \begin{pmatrix} \sum_n\sum_m 1 & \sum_n\sum_m m & \sum_n\sum_m n & \sum_n\sum_m m^2 & \sum_n\sum_m mn & \sum_n\sum_m n^2 \\ \sum_n\sum_m m & \sum_n\sum_m m^2 & \sum_n\sum_m mn & \sum_n\sum_m m^3 & \sum_n\sum_m m^2 n & \sum_n\sum_m mn^2 \\ \sum_n\sum_m n & \sum_n\sum_m mn & \sum_n\sum_m n^2 & \sum_n\sum_m m^2 n & \sum_n\sum_m mn^2 & \sum_n\sum_m n^3 \\ \sum_n\sum_m m^2 & \sum_n\sum_m m^3 & \sum_n\sum_m m^2 n & \sum_n\sum_m m^4 & \sum_n\sum_m m^3 n & \sum_n\sum_m mn^3 \\ \sum_n\sum_m mn & \sum_n\sum_m m^2 n & \sum_n\sum_m mn^2 & \sum_n\sum_m mn^3 & \sum_n\sum_m m^2 n^2 & \sum_n\sum_m m^2 n^2 \\ \sum_n\sum_m n^2 & \sum_n\sum_m mn^2 & \sum_n\sum_m n^3 & \sum_n\sum_m m^2 n^2 & \sum_n\sum_m mn^3 & \sum_n\sum_m n^4 \end{pmatrix} \cdot \begin{pmatrix} a_{00} \\ a_{10} \\ a_{01} \\ a_{20} \\ a_{11} \\ a_{02} \end{pmatrix} \tag{34}$$

It is noted that the square matrix in Equation (34) can be greatly simplified if the chosen polynomials are orthogonal over the discrete range chosen. However, in this case they are not quite orthogonal, but all odd summations do cancel out. Therefore:

$$\begin{pmatrix} \sum_n\sum_m f_{m,n} \\ \sum_n\sum_m mf_{m,n} \\ \sum_n\sum_m nf_{m,n} \\ \sum_n\sum_m m^2 f_{m,n} \\ \sum_n\sum_m mnf_{m,n} \\ \sum_n\sum_m n^2 f_{m,n} \end{pmatrix} = \begin{pmatrix} \sum_n\sum_m 1 & 0 & 0 & \sum_n\sum_m m^2 & 0 & \sum_n\sum_m n^2 \\ 0 & \sum_n\sum_m m^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sum_n\sum_m n^2 & 0 & 0 & 0 \\ \sum_n\sum_m m^2 & 0 & 0 & \sum_n\sum_m m^4 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sum_n\sum_m m^2n^2 & \sum_n\sum_m m^2n^2 \\ \sum_n\sum_m n^2 & 0 & 0 & \sum_n\sum_m m^2n^2 & 0 & \sum_n\sum_m n^4 \end{pmatrix} . \begin{pmatrix} \alpha_{00} \\ \alpha_{10} \\ \alpha_{01} \\ \alpha_{20} \\ \alpha_{11} \\ \alpha_{02} \end{pmatrix} \tag{35}$$

Equation (35) is further simplified using the known relationships:

$$\mathbf{A} = \mathbf{B}.\mathbf{C} \tag{36}$$

and

$$\mathbf{B}^{-1}.\mathbf{A} = \mathbf{C} \tag{37}$$

The dominant diagonal in matrix **B** simplifies the calculation of the matrix inversion $\mathbf{B}^{-1}$. Differentiation of equation (29) results in:

$$\left.\begin{aligned} \frac{\partial P}{\partial x} &= a_{10} + a_{11}y + 2a_{20}x = 0 \\ \frac{\partial P}{\partial y} &= a_{01} + a_{11}x + 2a_{02}y = 0 \end{aligned}\right\} \tag{38}$$

Equation (38) can explicitly be rewritten for the location of the extreme $(x_0, y_0) = (m_0\Delta, n_0\Delta)$ as:

$$x_0 = \frac{a_{10}(2a_{02} - a_{11})}{a_{11}^2 - 4a_{20}a_{02}} \text{ and } y_0 = \frac{a_{01}(2a_{20} - a_{11})}{a_{11}^2 - 4a_{20}a_{02}} \tag{39}$$

For M=N=1, the components of matrix **B** are:

$$\begin{aligned}
&\sum_{n=-1}^{1}\sum_{m=-1}^{1} 1 = 9 \\
&\sum_{n=-1}^{1}\sum_{m=-1}^{1} n^2 = \sum_{n=-1}^{1}\sum_{m=-1}^{1} m^2 = 6 \\
&\sum_{n=-1}^{1}\sum_{m=-1}^{1} n^2 m^2 = 4 \\
&\sum_{n=-1}^{1}\sum_{m=-1}^{1} n^4 = \sum_{n=-1}^{1}\sum_{m=-1}^{1} m^4 = 6
\end{aligned} \tag{40}$$

Similarly, for M=N=2 the components of matrix **B** are calculated as:

$$\begin{aligned}
&\sum_{n=-2}^{2}\sum_{m=-2}^{2} 1 = 25 \\
&\sum_{n=-2}^{2}\sum_{m=-2}^{2} n^2 = \sum_{n=-2}^{2}\sum_{m=-2}^{2} m^2 = 50 \\
&\sum_{n=-2}^{2}\sum_{m=-2}^{2} n^2 m^2 = 100 \\
&\sum_{n=-2}^{2}\sum_{m=-2}^{2} n^4 = \sum_{n=-2}^{2}\sum_{m=-2}^{2} m^4 = 170
\end{aligned} \tag{41}$$

The linear summations of the sampled function (matrix A in Equation (36)) can now be calculated.

$$\begin{pmatrix} \sum_n \sum_m f_{m,n} \\ \sum_n \sum_m m f_{m,n} \\ \sum_n \sum_m n f_{m,n} \\ \sum_n \sum_m m^2 f_{m,n} \\ \sum_n \sum_m mn f_{m,n} \\ \sum_n \sum_m n^2 f_{m,n} \end{pmatrix} \tag{42}$$

Explicitly, Equation (35) can be written as follows for the 3x3 neighbourhood (M=N=1):

$$\begin{pmatrix} \sum_n \sum_m f_{m,n} \\ \sum_n \sum_m m f_{m,n} \\ \sum_n \sum_m n f_{m,n} \\ \sum_n \sum_m m^2 f_{m,n} \\ \sum_n \sum_m mn f_{m,n} \\ \sum_n \sum_m n^2 f_{m,n} \end{pmatrix} = \begin{pmatrix} 9 & 0 & 0 & 6 & 0 & 6 \\ 0 & 6 & 0 & 0 & 0 & 0 \\ 0 & 0 & 6 & 0 & 0 & 0 \\ 6 & 0 & 0 & 6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 4 & 4 \\ 6 & 0 & 0 & 4 & 0 & 6 \end{pmatrix} \cdot \begin{pmatrix} a_{00} \\ a_{10} \\ a_{01} \\ a_{20} \\ a_{11} \\ a_{02} \end{pmatrix} \tag{43}$$

and matrix inversion of Equation (43) gives:

$$\begin{pmatrix} a_{00} \\ a_{10} \\ a_{01} \\ a_{20} \\ a_{11} \\ a_{02} \end{pmatrix} = \frac{1}{12} \begin{pmatrix} 12 & 0 & 0 & -4 & 0 & -12 \\ 0 & 2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 & 0 \\ -12 & 0 & 0 & 6 & 0 & 12 \\ 4 & 0 & 0 & 0 & 3 & -6 \\ -4 & 0 & 0 & 0 & 0 & 6 \end{pmatrix} \cdot \begin{pmatrix} \sum_n \sum_m f_{m,n} \\ \sum_n \sum_m m f_{m,n} \\ \sum_n \sum_m n f_{m,n} \\ \sum_n \sum_m m^2 f_{m,n} \\ \sum_n \sum_m mn f_{m,n} \\ \sum_n \sum_m n^2 f_{m,n} \end{pmatrix} \tag{44}$$

Given the foregoing, curve fitting may be used to locate the extremes of the error function. An embodiment of an implementation of an extreme locater 50 operating using the curve fitting method is shown in Fig. 9.

A minimum neighbourhood locater 97 finds the smallest one of the error coefficients output from the error function calculator 40. The minimum neighbourhood locater 90 further stores the coefficients in a number of line stores 91 (which preferably holds between 3 and 5 lines). When a new minimum is located, the locator 97 writes the 3x3 or 5x5 coefficients surrounding the minimum to a Minimum Neighbourhood buffer 92.

The buffer 92 outputs to an image moment calculator 93 which calculates the following terms:

$$\begin{pmatrix} \sum_n \sum_m f_{m,n} \\ \sum_n \sum_m m f_{m,n} \\ \sum_n \sum_m n f_{m,n} \\ \sum_n \sum_m m^2 f_{m,n} \\ \sum_n \sum_m mn f_{m,n} \\ \sum_n \sum_m n^2 f_{m,n} \end{pmatrix} \tag{45}$$

which are seen as one primary component of Equation (44).

A matrix multiplier 94 multiplies the terms of equation (45) with the known matrix coefficients derived from Equation (40) or (41), and which are stored in a matrix coefficients memory 95. The coefficients a_{00}, a_{10}, a_{01}, a_{20}, a_{11}, and a_{02} can then be calculated using Equation (44).

A displacement calculator 96 accepts the outputs of the matrix multiplier 94 and implements Equation (39) (reproduced below) using adders, multipliers and dividers to implement the desired functions:

$$x_0 = \frac{a_{10}(2a_{02} - a_{11})}{a_{11}^2 - 4a_{20}a_{02}} \text{ and } y_0 = \frac{a_{01}(2a_{20} - a_{11})}{a_{11}^2 - 4a_{20}a_{02}} \tag{39}$$

The outputs of the displacement calculator 96 are the horizontal and vertical displacements (x_o, y_o) of the input images g_1 and g_2 of Fig. 4 in relation to each other. The

horizontal and vertical displacements (x_o,y_o) are then supplied to subsequent devices as a motion vector of the block of images g_1 and g_2. The motion vector may be applied or utilized as required to perform a variety of functions, such as those traditionally associated with motion vectors.

Accordingly, by utilizing sub-frame or sub-field sampling of an image through the arrangement of Fig. 5, it is thus possible to obtain a motion vector from the equivalent of single prior art image sample, whereas according to prior art configurations, at least two traditional samples would be required. Thus the described embodiment provides for an estimation of motion blur for each traditional image capture, be it a frame or an interlaced field.

The above can be readily seen from Figs. 10A to 10E. Fig. 10A shows a prior art video signal 100 where an image frame is captured during period 102 and output from the sensor during a period 104 prior to the next frame 102 being captured. Fig. 10B shows a similar signal 106 for an interlaced frame where a first field 108 is captured and output over a period 110. A second field 112 is captured and output over a period 114 prior to the first field of the next frame being captured.

According to an embodiment of the invention, as shown in Fig. 10C, a first image 122 is captured followed by a second image 124, the second image 124 for example corresponding to the first field 108 of Fig. 10B. The data of the two images 122 and 124 is output during a period 126 before images 128 and 130 are captured for the next field and output during the period 132.

Whilst Fig. 10C shows the motion blur images being captured one immediately after the other, such need not always be the case. As seen in Fig. 10D, a capture sequence 134 includes the capture of a first blur image 136 overlapping with the capture of a second blur image 138. In Fig. 10E, a capture sequence 140 involves capturing one image 142 over a period twice that of another image 144.

The multiple capture ability of the described arrangement derives from the duplication of the switching arrangements 66 of Fig.5. As a consequence, further duplication can result in further images being captured in association. Such may be useful in high speed photography of transient events where the capture time permits capturing the event, but where the time

required to output buffer the image data exceeds the time available to enable use of traditional video systems.

A specific advantage afforded by the present invention is that the image sensor 10 used to capture the images from which motion blur is estimated, can be implemented in a number of configurations. In one configuration, shown in Fig. 11, the image sensor 10 can be the sensor from which the image to be ultimately displayed or otherwise reproduced is obtained. There, a video camera 150 is illustrated which includes a lens 152 and a charge-coupled device sensor 154 constructed according to the arrangement of Fig. 5. The sensor 154 outputs the two blur images g_1 and g_2 to a motion blur estimation unit 156 according to the above description. The image g_2 also forms an output image of the camera 150 and is combined in a summer with motion vector meta-data 164 output from the unit 156. A delay 158 such as a frame store may be used to ensure that the motion blur data is synchronised to the corresponding output image frame. The combined signal may be stored on a recording medium, such as tape or disk, for output 168 from the camera 150.

Alternatively, as shown in the digital video camera 170 of Fig. 12, the image sensor 10 can be additional to that used to form the image output. In Fig. 12, the camera 170 includes a traditional lens 180 and CCD sensor 182 for capturing images in a traditional fashion. A further image sensor 174 constructed according to the principles of Fig. 5 is provided and associated with a corresponding lens 172 for detection of image motion blur. Where desired, the camera 170 may include only a single lens (not illustrated) and associated optics for directing the image being viewed to each of the sensors 174 and 182. As seen from Fig. 12, the sensor 174 is depicted smaller than the sensor 182. In this regard, since motion blur is generally regional within an image, rather than randomised on a pixel-by-pixel basis, a lower resolution sensor may be used. Such facilitates optimising the computational complexity of the motion estimation unit 176 by simplifying the correlations and transforms where appropriate. A synchronisation unit 184 is provided to ensure the appropriate motion vector meta-data 178 is matched with the corresponding image output from the sensor 182. Other components of the camera 170 perform corresponding functions to those of Fig. 11.

The foregoing describes only some embodiments of the present invention, and modifications and/or changes can be made thereto without departing from the scope and spirit of the invention, the embodiments being illustrative and not restrictive.

Claims: The claims defining the invention are as follows

1A. Apparatus for estimating motion of a moving image, said apparatus comprising:

an image sensor for capturing pixels of at least first and second images in which one of said images is sampled during a formation of at least one other of said images;

means for comparing said images to determine at least one motion vector for association with one of said images.

1B. Apparatus for estimating motion of a moving image, said apparatus comprising:

an image sensor for capturing pixels of at least first and second images in which one of said images is sampled after sampling of at least one other of said images, the sampling of said one image occurring before an outputting from said sensor of image data of said other image;

means for comparing said images to determine at least one motion vector for association with one of said images.

1C. Apparatus for estimating motion of a moving image, said apparatus comprising:

an image sensor for capturing pixels of at least first and second images characterised in that images data of each of said images is acquired prior to an outputting of said image data from said sensor;

means for comparing said images to determine at least one motion vector for association with one of said images.

2. Apparatus according to claim 1A, 1B or 1C wherein said image sensor comprises, for each said pixel:

an pixel sensor; and

pixel sampling means for sampling a value of said pixel sensor at a time corresponding to each of said images.

3. Apparatus according to claim 2 wherein said image sensor further comprises, for each said pixel, reset means for resetting the corresponding said pixel sensor after sampling of each of said images.

4. Apparatus according to claim 3 wherein said image sensor comprises a pixel bus configured for sequential coupling to a plurality of said pixel sampling means, and a switching arrangement associated with said pixel bus, said switching arrangement comprising a least first and second storage devices corresponding to each of said images and each being configured to store temporal value of said pixel sensor at said corresponding time, and switching means for outputting said temporal values to represent corresponding pixel values of said images of said images.

5. Apparatus according to claim 4 wherein said pixel sensor comprises a cell capacitor, a voltage upon said cell capacitor being modified by exposure of said pixel sensor to an image to be captured, and said storage devices comprise storage capacitors.

6. Apparatus according to claim 4 wherein said image sensor comprises plural said pixel buses and associated switching arrangements, each associated with plural of said pixel sensors and corresponding pixel sampling means thereby forming a matrix of said pixel sensors.

7. Apparatus according to claim 1A, 1B or 1C, wherein at least said second image comprises an exposure duration greater than that of said first image, thereby providing at least said second image as blurred representation of said first image where a target of said images presents motion.

8. Apparatus according to claim 7 wherein said second image is a predetermined integer multiple of an exposure duration of said first image.

9. Apparatus according to claim 7, wherein exposure durations of said first and second images overlap.

10. Apparatus according to claim 1A, 1B or 1C,wherein said means for comparing comprises:

an auto-correlator for calculating auto-correlation of said first image; and

a cross-correlator for calculating cross-correlation between said first image and said second image; and

error means for minimising an error function between said auto-correlation and said cross-correlation.

11. An image sensor according to claim 10 wherein said error means comprises an error function calculator for determining an error function value at each pixel location between said auto-correlation and said cross-correlation, and an extreme locator for thresholding said error function value at each said pixel location to provide movement parameters corresponding to each said pixel location.

12. An image sensor according to claim 11 wherein said movement parameters comprise direction and magnitude.

13. An image sensor for capturing pixels of at least first and second images characterised in that at least one of said images is sampled during a formation of at least one other of said images;

14. An image sensor according to claim 13 wherein said at least two captured images have each have a corresponding start exposure time and different end exposure times.

15. An image sensor according to claim 14, said image sensor comprising:

an array of pixel cells, each said pixel cell for storing an electrical charge equivalent of an intensity of light to which said cell is exposed; and

at least two arrays of capacitors, each of said arrays of capacitors comprises capacitors electrically connected with corresponding pixel cells;

wherein at each of said end exposure times said array of capacitors is arranged to store the charge of said array of pixel cells at said end exposure time.

16. Apparatus for capturing a moving image, said apparatus comprising:

at least one image sensor according to any one of the preceding claims;

means for controlling said image sensor to capture a sequence of said first and second images and for determining a motion vector relating to image blur between each pair of said first and second images in said sequence;

means for combining the corresponding said motion vector with at least one of said first and second images in said sequence to output a sequence of images each having an associated motion vector.

17. Apparatus according to claim 16 wherein said sequence of images output from said apparatus comprise a sequence of said second images.

18. Apparatus for capturing a moving image, said apparatus comprising:

a first image sensor, said first image sensor being configured according to any one of claims 1A to 15;

means for controlling said first image sensor to capture a first sequence of said first and second images and for determining a motion vector relating to image blur between each pair of said first and second images in said sequence;

a second image sensor for capturing a second sequence of images to be output from said apparatus;

means for combining each said motion vector of said first sequence with a corresponding image in said second sequence to output from said apparatus a sequence of images each having an associated motion vector.

19. Apparatus according to claim 18 wherein said images captured by said second sensor have a resolution exceeding that of those captured by said first sensor.

20. Apparatus according to claim 18 or 19, said apparatus comprising optical means for viewing a scene to be captured and presenting said scene to each of said sensors.

21. Apparatus according to any one of claims 16 to 20 further comprising synchronisation means for synchronising said motion vectors with corresponding images forming said output sequence.

22. Apparatus for estimating motion of an image from a first and a second blurred image, said apparatus being substantially as described herein with reference to any one of the embodiments as that embodiment is illustrated in the accompanying drawings.

23. An image sensor for capturing at least two captured images of an image, said image sensor being substantially as described herein with reference to Figs 5 and 6 of the accompanying drawings.

DATED this FOURTEENTH Day of DECEMBER 1999
Canon Kabushiki Kaisha
Patent Attorneys for the Applicant/Nominated Person
SPRUSON & FERGUSON

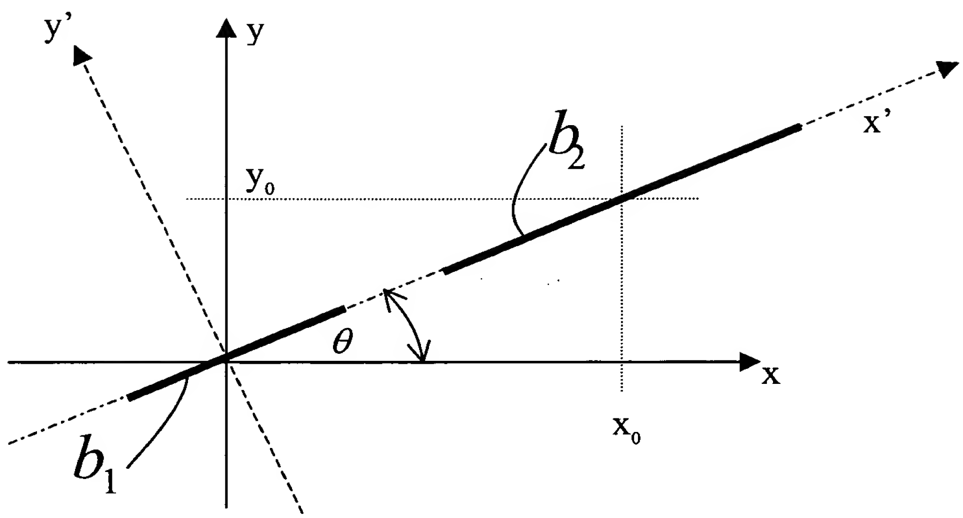


Fig. 1

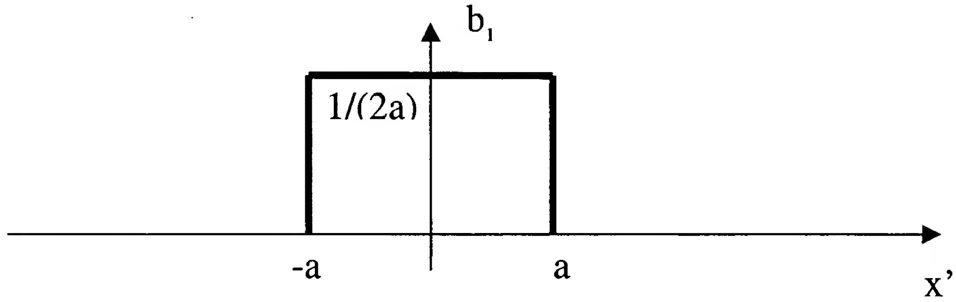


Fig 2A

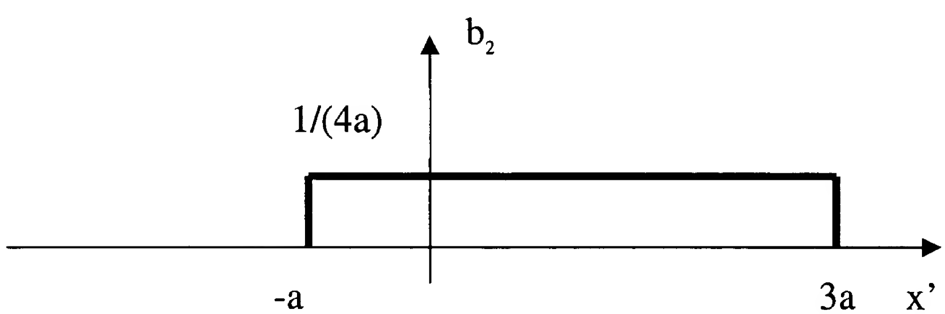


Fig 2B

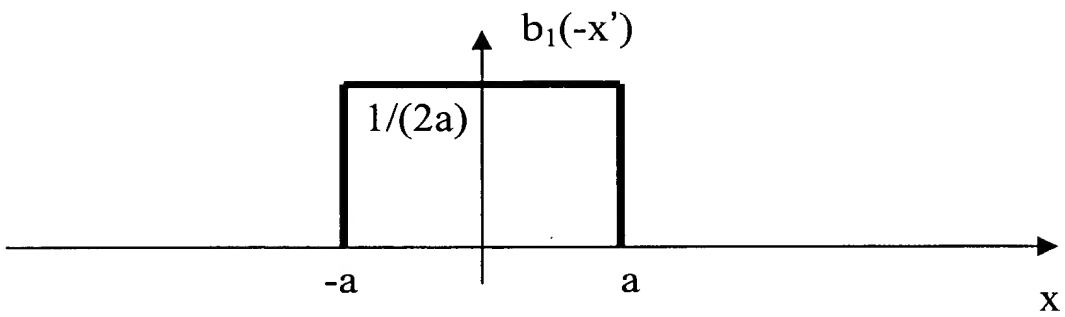


Fig 3A

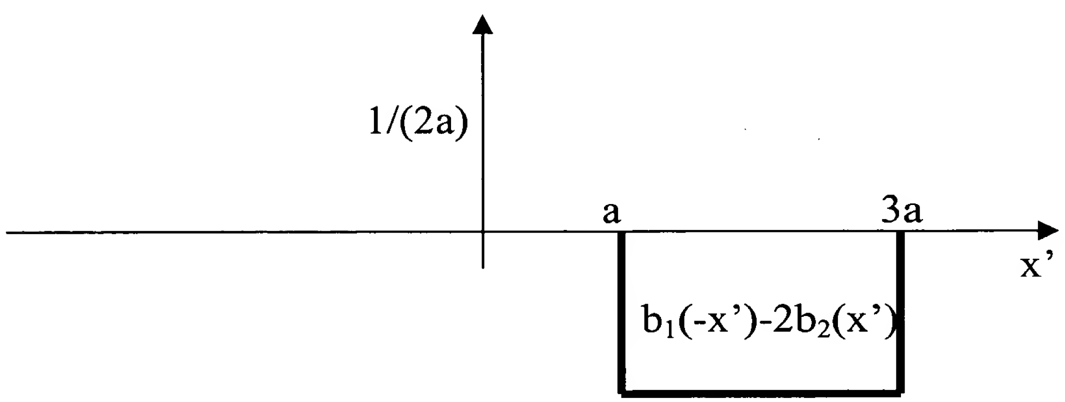


Fig 3B

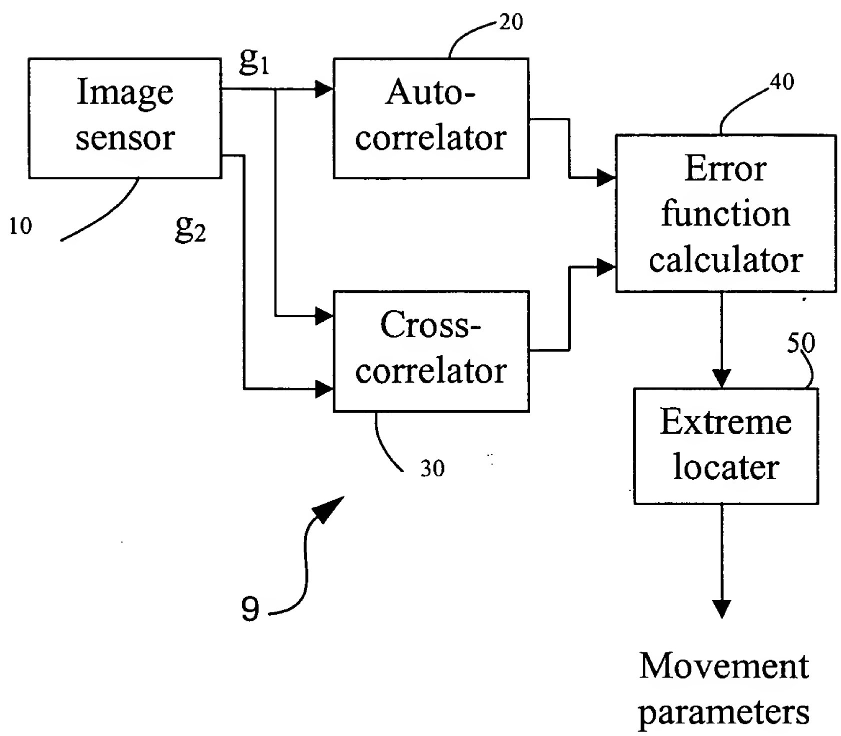


Image sensor
g1
g2
10
Auto-correlator
20
Cross-correlator
30
Error function calculator
40
Extreme locater
50
Movement parameters
9

Fig. 4

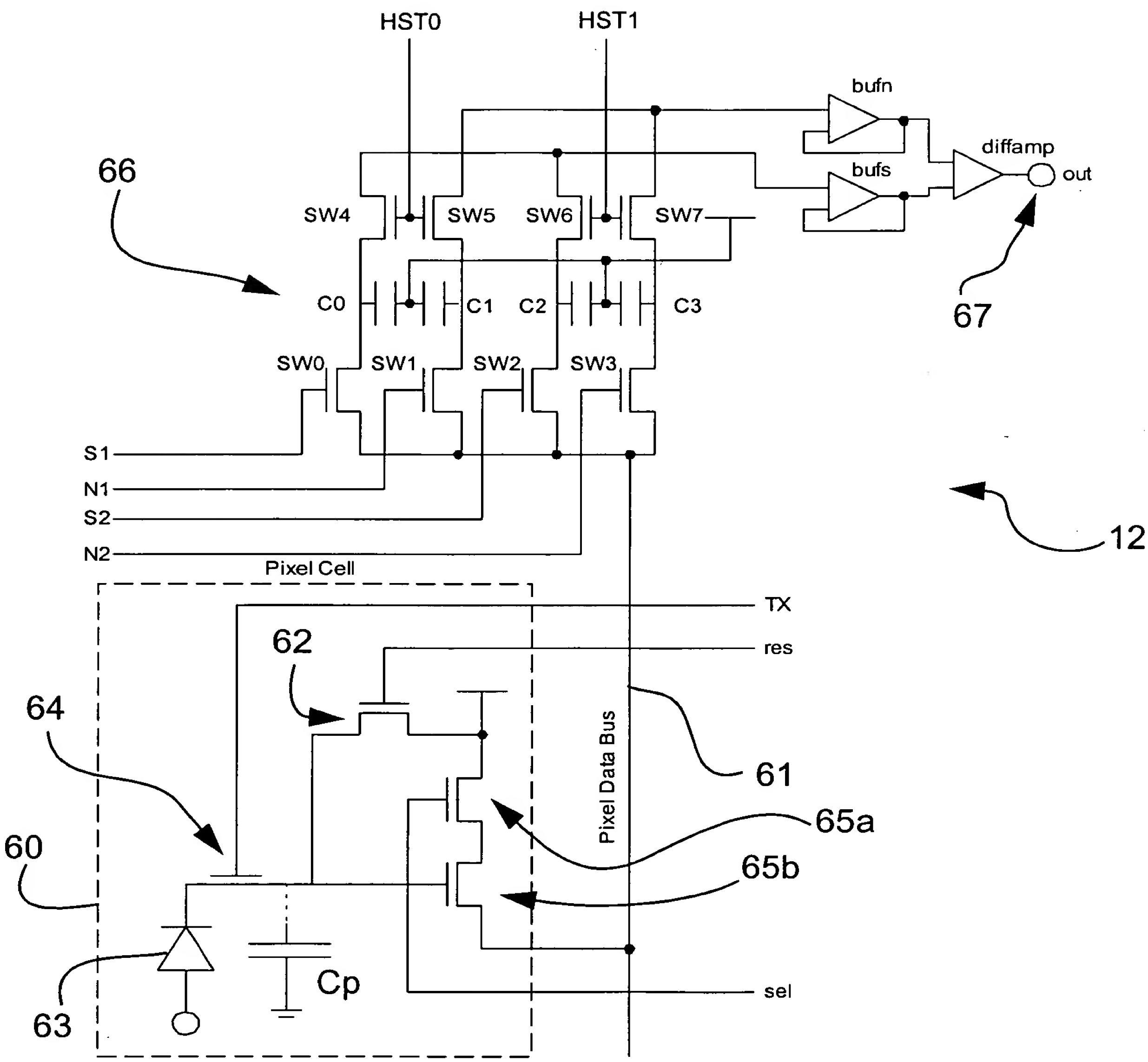

HST0
HST1
bufn
bufs
diffamp
out
66
67
SW4
SW5
SW6
SW7
C0
C1
C2
C3
SW0
SW1
SW2
SW3
S1
N1
S2
N2
12
Pixel Cell
TX
res
62
64
61
Pixel Data Bus
65a
65b
60
63
Cp
sel

Fig. 5

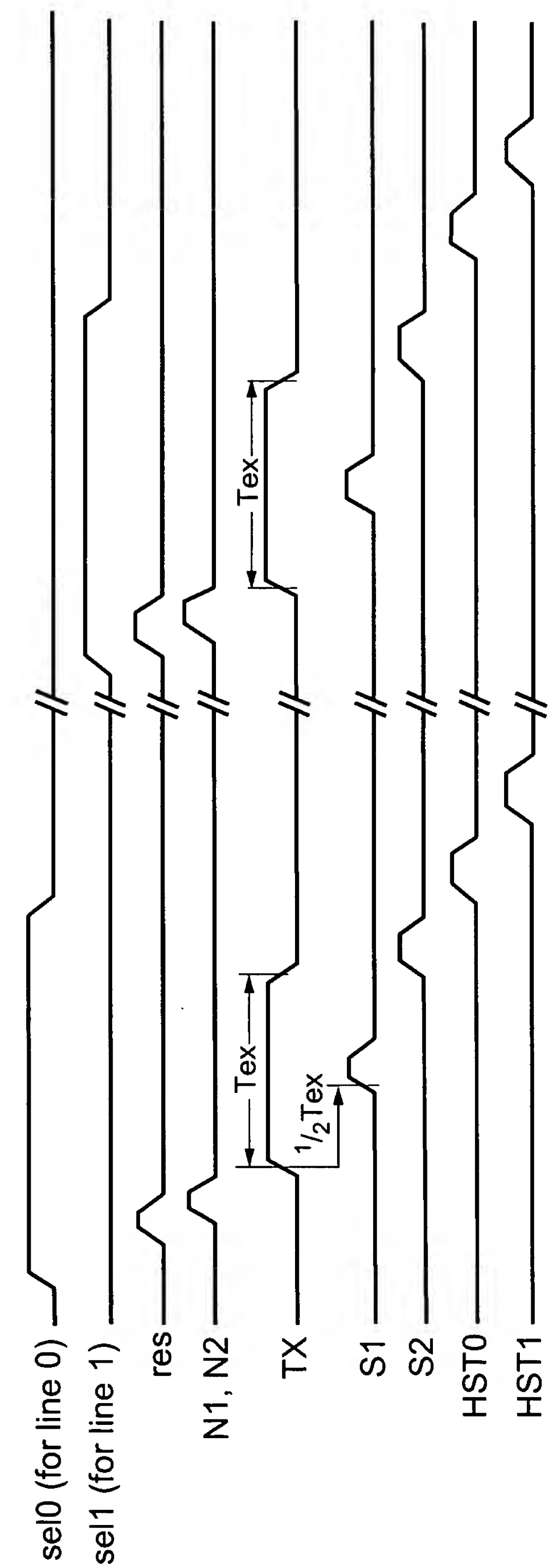

sel0 (for line 0)
sel1 (for line 1)
res
N1, N2
TX
S1
S2
HST0
HST1
Tex
Tex
1/2Tex

Fig. 6

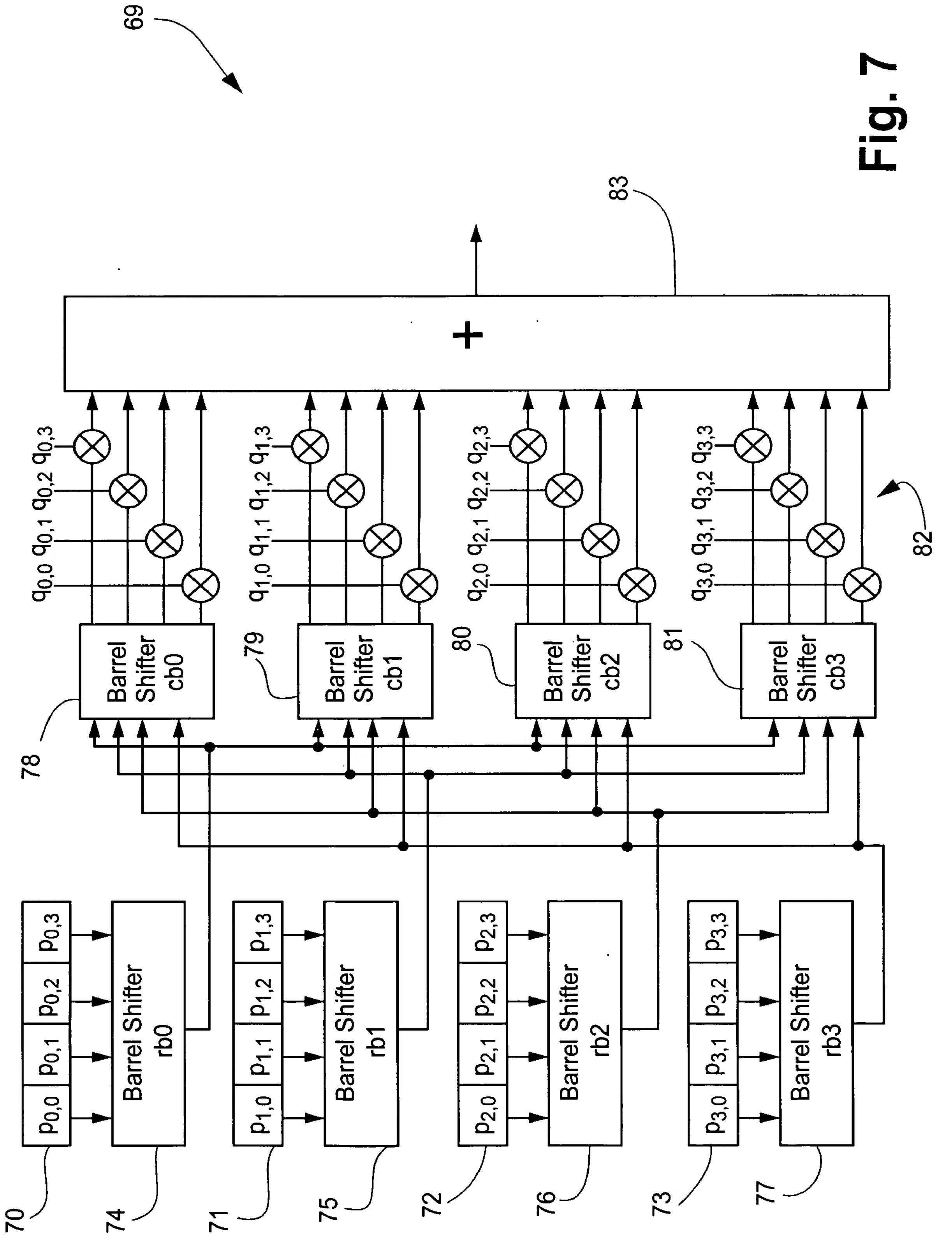

69
83
+
82
$q_{0,0}$ $q_{0,1}$ $q_{0,2}$ $q_{0,3}$
$q_{1,0}$ $q_{1,1}$ $q_{1,2}$ $q_{1,3}$
$q_{2,0}$ $q_{2,1}$ $q_{2,2}$ $q_{2,3}$
$q_{3,0}$ $q_{3,1}$ $q_{3,2}$ $q_{3,3}$
Barrel Shifter cb0
Barrel Shifter cb1
Barrel Shifter cb2
Barrel Shifter cb3
78
79
80
81
$p_{0,0}$ $p_{0,1}$ $p_{0,2}$ $p_{0,3}$
$p_{1,0}$ $p_{1,1}$ $p_{1,2}$ $p_{1,3}$
$p_{2,0}$ $p_{2,1}$ $p_{2,2}$ $p_{2,3}$
$p_{3,0}$ $p_{3,1}$ $p_{3,2}$ $p_{3,3}$
Barrel Shifter rb0
Barrel Shifter rb1
Barrel Shifter rb2
Barrel Shifter rb3
70
74
71
75
72
76
73
77

Fig. 7

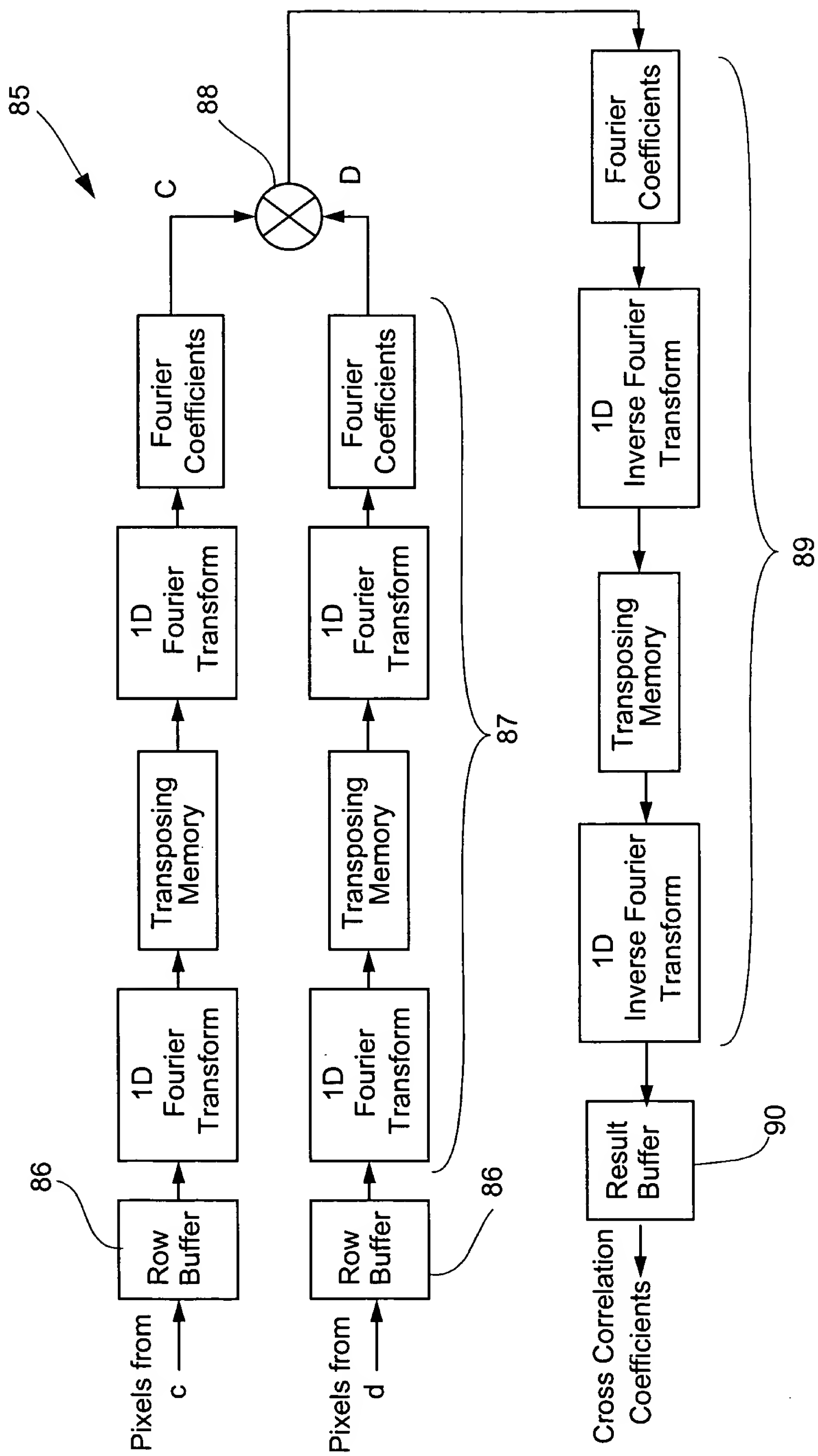
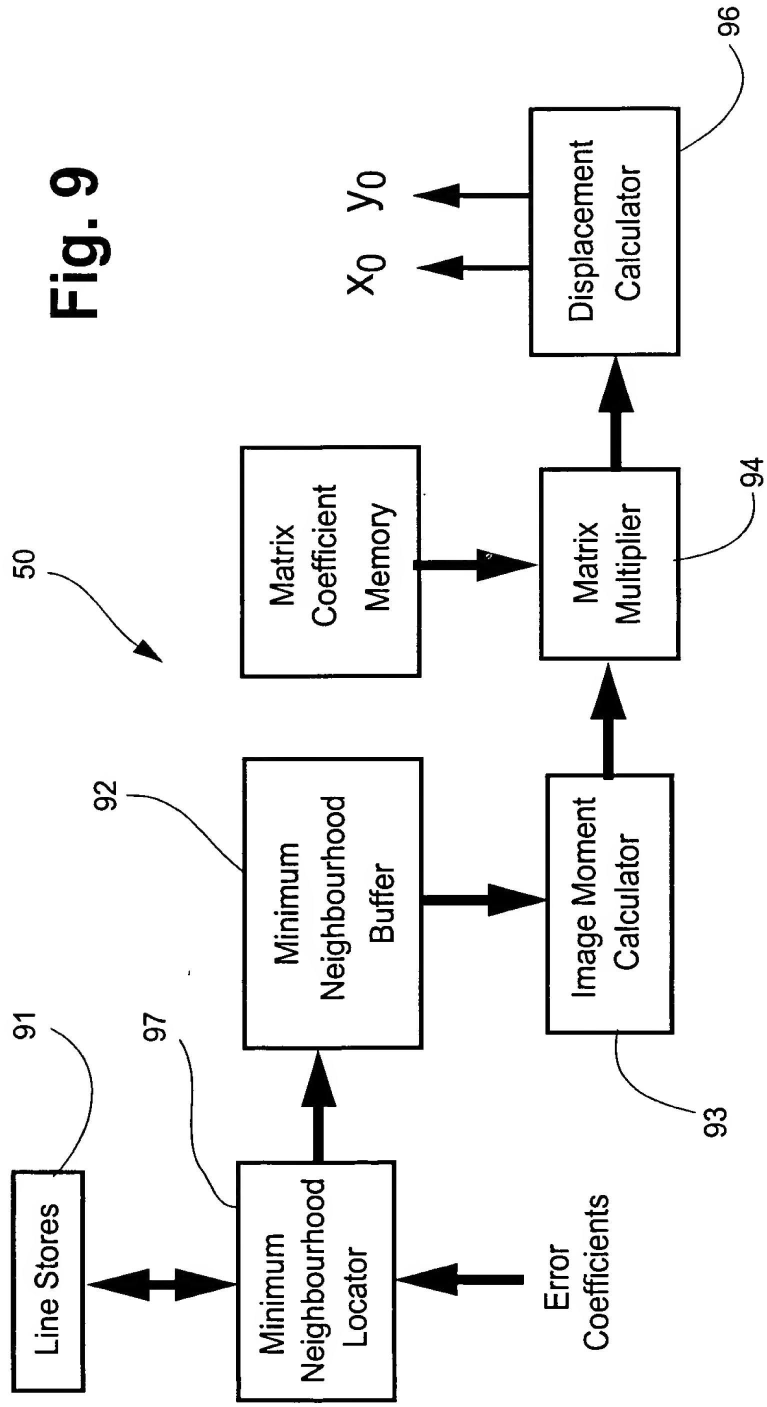

85
Pixels from c
Row Buffer
86
1D Fourier Transform
Transposing Memory
1D Fourier Transform
Fourier Coefficients
C
88
Pixels from d
Row Buffer
86
1D Fourier Transform
Transposing Memory
1D Fourier Transform
Fourier Coefficients
D
87
Fourier Coefficients
1D Inverse Fourier Transform
Transposing Memory
1D Inverse Fourier Transform
89
Result Buffer
90
Cross Correlation Coefficients

Fig. 8



Line Stores
Minimum Neighbourhood Locator
Minimum Neighbourhood Buffer
Image Moment Calculator
Matrix Coefficient Memory
Matrix Multiplier
Displacement Calculator
Error Coefficients
x_0
y_0
91
97
92
93
50
94
96

Fig. 9

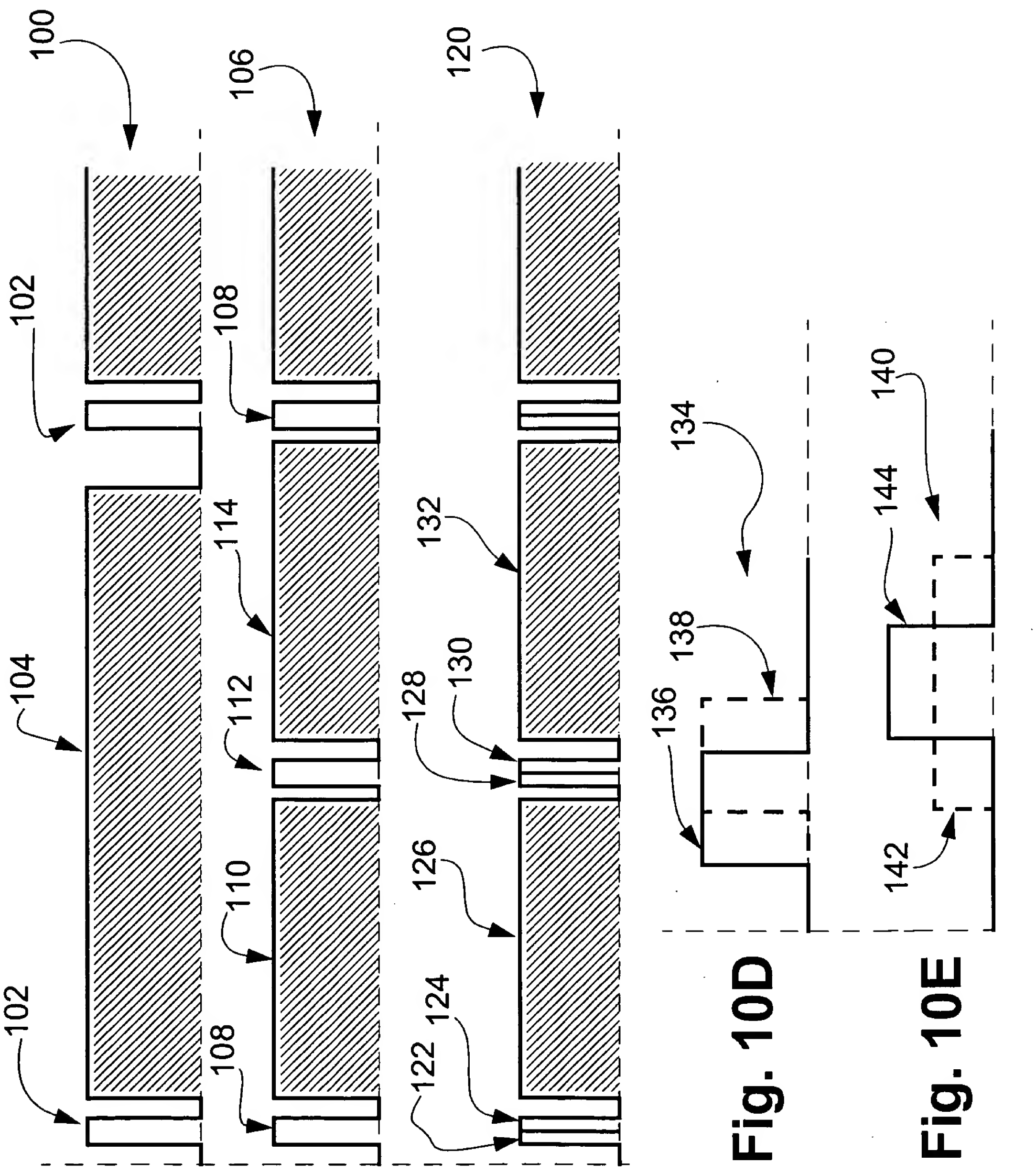


Fig. 10A (Prior Art)
Fig. 10B (Prior Art)
Fig. 10C
Fig. 10D
Fig. 10E

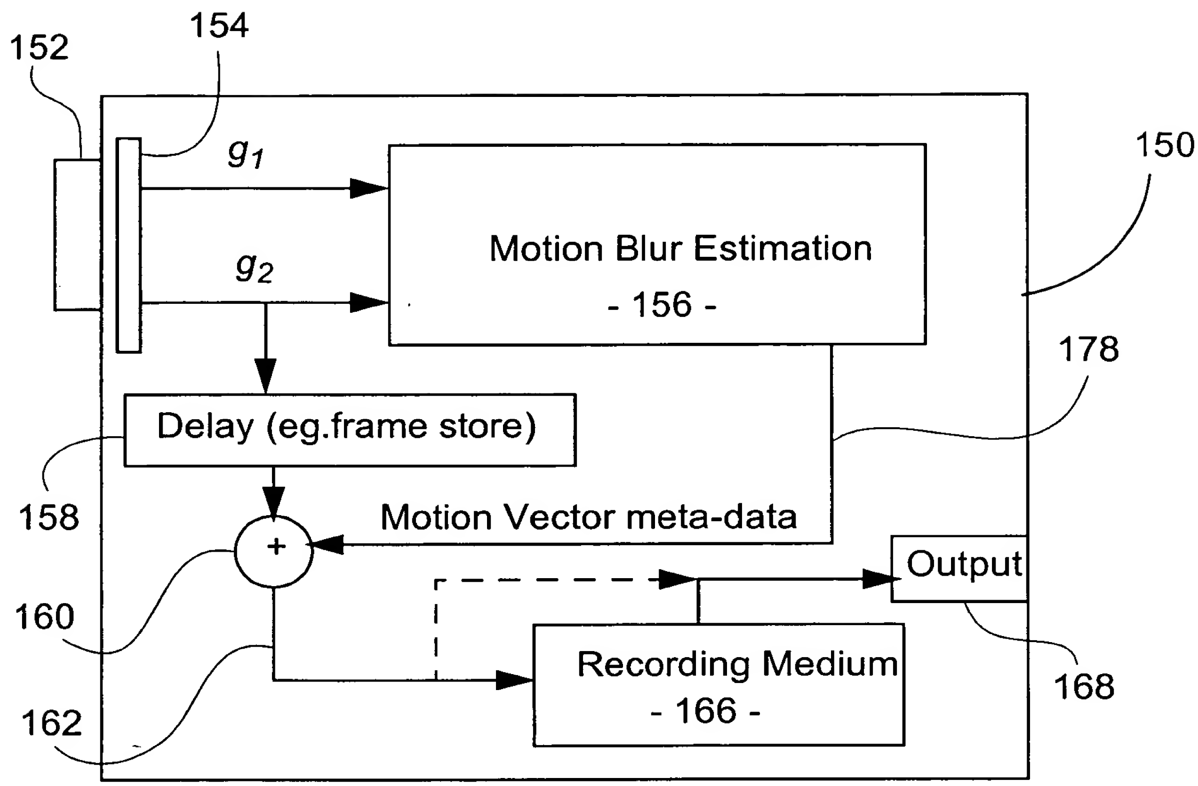

152
154
150
g_1
g_2
Motion Blur Estimation
- 156 -
178
Delay (eg.frame store)
158
Motion Vector meta-data
+
Output
160
Recording Medium
- 166 -
168
162

Fig. 11

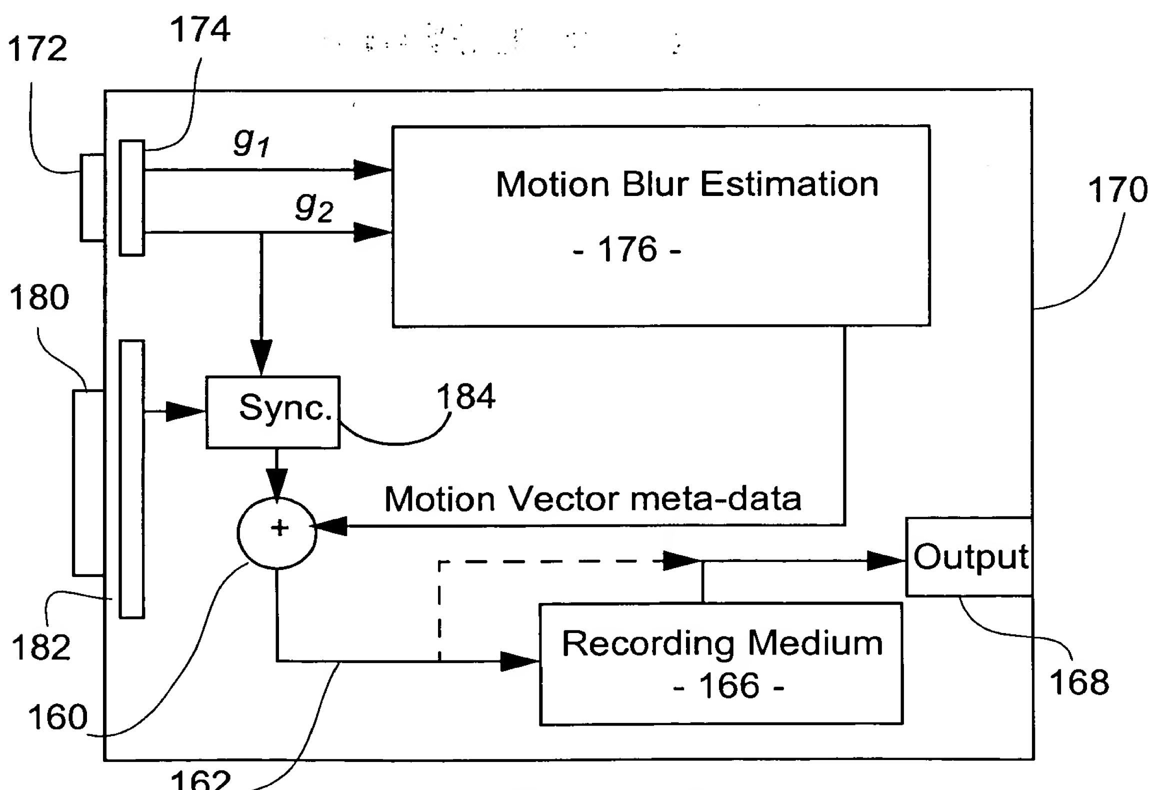

172
174
g_1
g_2
Motion Blur Estimation
- 176 -
170
180
Sync.
184
Motion Vector meta-data
+
Output
182
Recording Medium
- 166 -
168
160
162

Fig. 12

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